Reference 54

Two-dimensional photonic crystal Mach–Zehnder interferometers

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Mach–Zehnder interferometers were fabricated from suspended membrane photonic crystal waveguides. Transmission spectra were measured and device operation was shown to be in agreement with theoretical predictions. © *2004 American Institute of Physics.*
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Planar photonic crystal waveguide (PCWG) technology has the potential to be a fundamental building block for future optical integrated circuits. Some of this potential arises from the ability to form small turning radius waveguide bends and wide angle *Y* branches[1] leading to the possibility of dense device integration. There have been many experimental demonstrations of two-dimensional photonic crystal waveguides recently including quantitative optical loss measurements.[2–4] However, there have been few demonstrations published to date of photonic crystal waveguide bends and branches.[5–7] In this letter, we report on a demonstration of Mach–Zehnder interferometers formed in two-dimensional photonic crystals.

In this work we have fabricated Mach–Zehnder interferometers in two-dimensional photonic crystals with a range of path length differences between the arms of the interferometer. We expect therefore that the intensity transmitted through the interferometers will exhibit oscillations in the transmitted intensity as a function of the optical frequency with a period that depends on the path length difference and the propagation coefficient. The finite element method was used to calculate the band structure of the even guided mode for the PCWGs. Figure 1(a) shows the calculated dispersion relations of guided modes of waveguides with ratios of the hole radius to lattice constant, r/a, of 0.27, 0.30, and 0.33. Only the lowest order guided mode is included in this figure. In this work, we intend to operate the fabricated Mach–Zehnder interferometers in the spectral region in which there is very little chromatic dispersion. This simplifies the data analysis because we expect a fixed propagation coefficient and therefore a fixed oscillation period in the transmitted intensity over the wavelength range of operation. From the data in Fig. 1(a), for an r/a value of 0.3 and a lattice constant value of 420 nm, this low chromatic dispersion region corresponds to the wavelength range of 1500–1550 nm and propagation coefficient in the range of 0.30–0.35. The experimental data in each case was taken in this low chromatic dispersion region. The group index can be obtained by differentiating the dispersion relation in Fig. 1(a) and is plotted as a function of normalized wavelength in Fig. 1(b). Included

in this figure are traces for different values of r/a. The r/a ratio is one of the least tightly controlled lattice parameters in our fabrication process. We have collected data from a number of devices. Each of these devices has a constant r/a
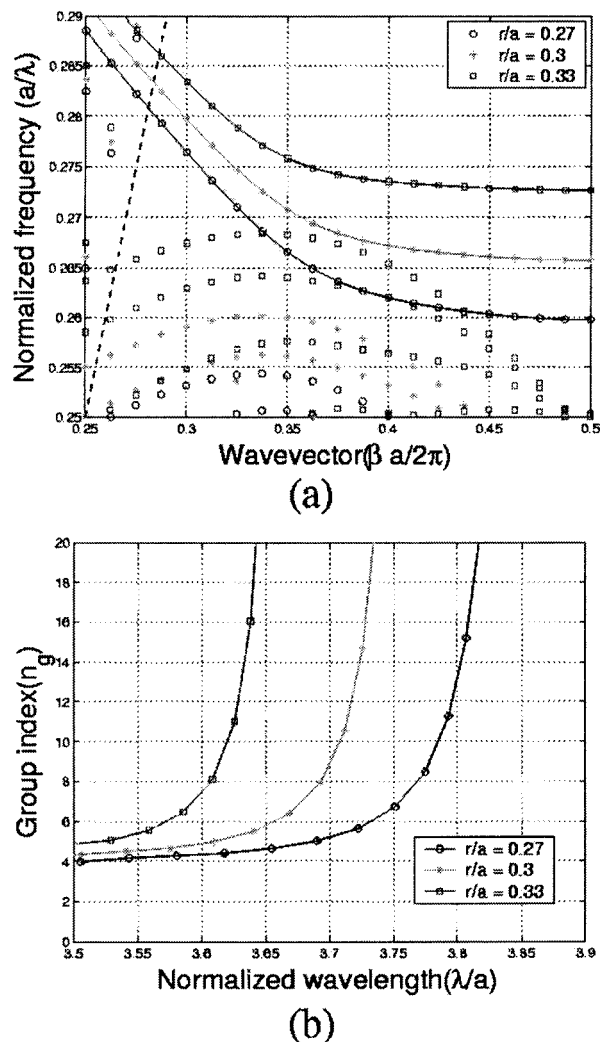

FIG. 1. (a) Finite element method (FEM) band structure calculation of PCWG. The waveguide modes are indicated by solid lines, while the photonic crystal cladding band edge states do not have lines through them. (b) Group index from FEM band structure calculation of PCWG with different r/a, 0.27, 0.30, and 0.33.

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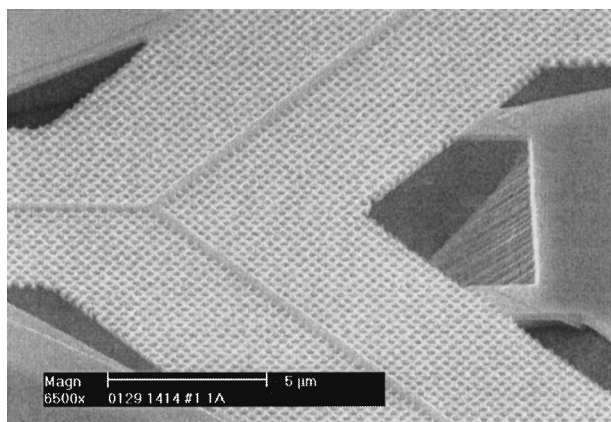| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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FIG. 2. SEM micrograph showing the part of the Mach–Zehnder structure near one of the Y branches.

value. The range of r/a values of these devices is between 0.28 and 0.32. Based on the data in Fig. 1(b), we therefore expect that we should experimentally observe values of the group index between about 5 and 7.

The Mach–Zehnder interferometers were formed by linear defects in a two-dimensional triangular lattice photonic crystal that was patterned into a suspended $In_{0.74}Ga_{0.26}As_{0.56}P_{0.44}$ membrane. This layer was deposited on an InP substrate by metalorganic chemical vapor deposition. The photonic crystal was then defined by electron-beam lithography in 2% polymethylmethacrylate (PMMA). After developing the resist, the PMMA was used as a mask to transfer the pattern into a Au/Cr layer using an Ar+ beam milling step. This metal layer was then used as a mask in an electron cyclotron resonance (ECR) etch to transfer the pattern into the semiconductor. The ECR etch was done using a $CH_4/H_2/Ar$ gas chemistry with flow rates of 38.3/24.2/12.0 sccm respectively. The suspended membrane was formed using a 4/1 HCl/H_2O wet chemical etch at 0 °C for 8–12 min.[8] Open areas were defined outside of the photonic crystal waveguide cladding in these devices in order to facilitate the formation of suspended membranes. Devices having path length differences between the two arms of 0, 75, and 121 μm were fabricated for this work. The devices reported here have a lattice constant, a, of 420 nm and hole radius to lattice constant ratio, r/a, of 0.28–0.32. The interferometers had 15 periods of photonic crystal cladding on each side of the waveguide core. Figure 2 shows a scanning electron microscope (SEM) image of a fabricated PCWG Mach–Zehnder structure near one of the Y branches. The fabricated PCWG Mach–Zehnder structures were cleaved at both ends. Figure 3 shows SEM micrographs of three such devices before cleaving.

A lensed fiber was used to launch transverse electric polarized light from a tunable laser into the PCWG Mach–Zehnder interferometers, and a cleaved single mode fiber was used to collect the output signal. We observed the expected oscillations in the transmitted intensity as the wavelength of the tunable laser was varied. Figure 4 shows the Fourier transform of the experimental transmission data as a function of the inverse optical wavelength, $1/\lambda$, for devices with path length differences of: 0 μm (a), 75 μm (b), and 121 μm (c). The unit associated with the transformed data is microns and the abscissas are scaled so that the values rep-

FIG. 3. SEM images of the Mach–Zehnder PCWG with path-length differences of: (a) 0 μm, (b) 75 μm, and (c) 121 μm.

resent the product of the group index and the path length difference, ΔL, of the Mach–Zehnder interferometer. Peaks in the Fourier transforms corresponding to oscillations in transmitted intensity due to Mach–Zehnder interferences show up clearly at the expected locations. Figures 4(b) and 4(c) show the strong contributions at 502 and 637 μm, which correspond to the group indices of $n_g = 6.7$ and 5.3, for path length differences of 75 and 121 μm, respectively. The group indices obtained from the measured transmission spectra fall within the range of values predicted by the finite-element-method results in Fig. 1(b). There is also a second peak in the Fourier spectrum shown in Fig. 4(c). This peak at 2230 μm is attributed to the Fabry–Pérot mode that exists in the substrate between the cleaved facets of the Mach–Zehnder interferometer. We have verified that this peak originates from
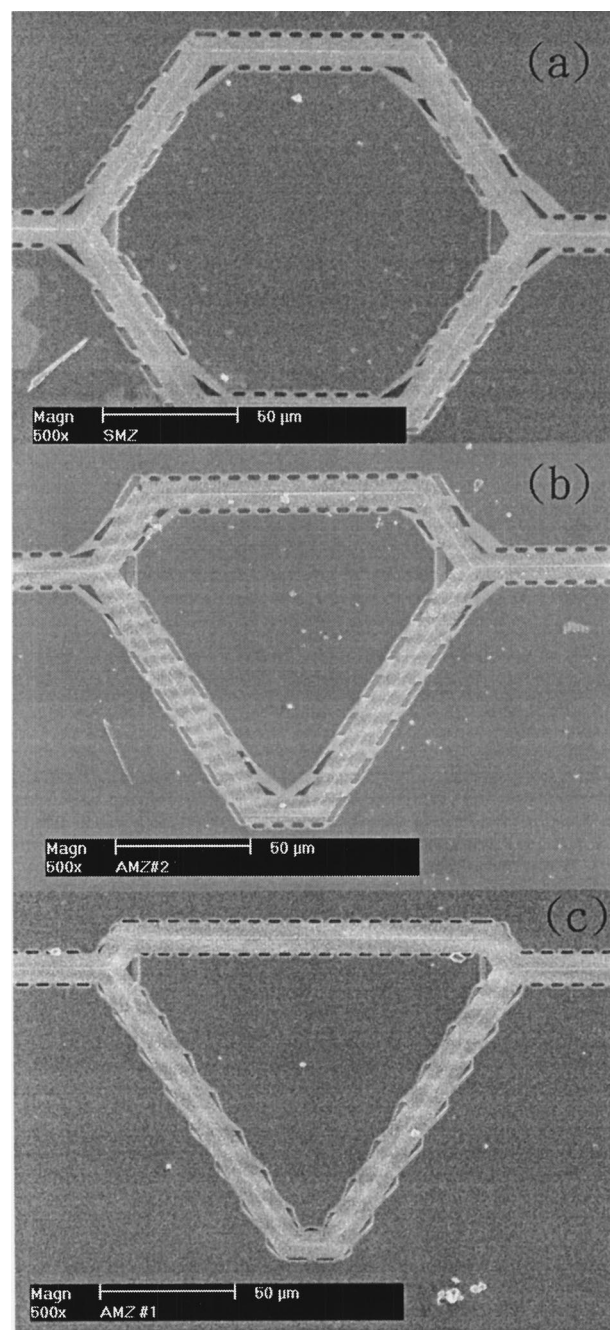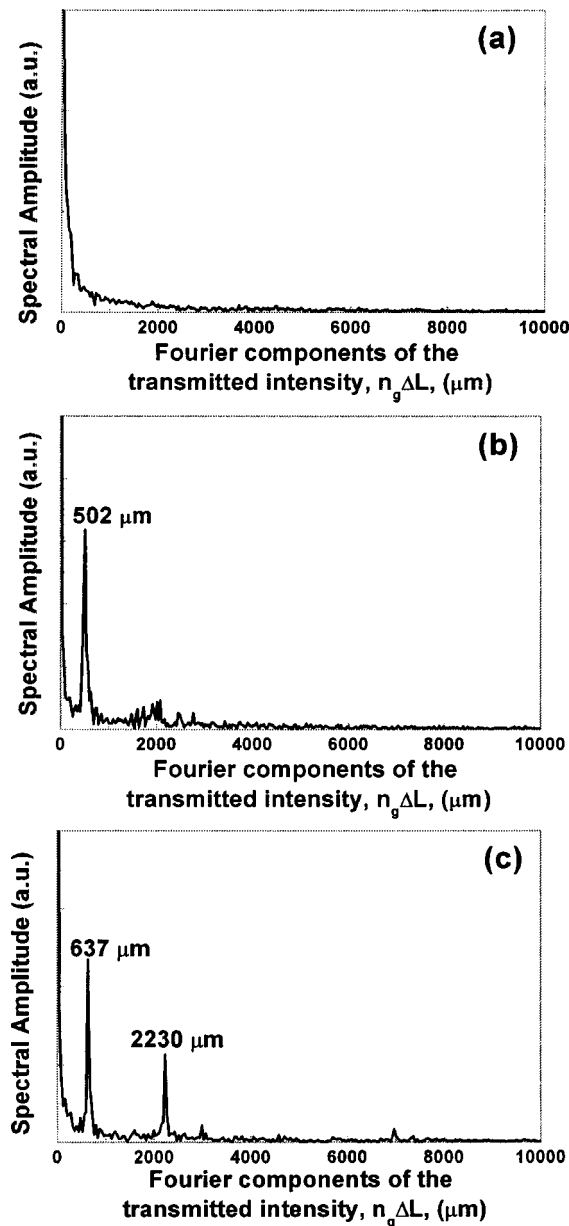
FIG. 4. Fast Fourier transform spectra of the transmitted intensity through Mach–Zehnder PCWGs with branch-path differences: (a) 0 μm, (b) 75 μm, and (c) 121 μm.

ric Mach–Zehnder was also fabricated and the transmitted intensity as a function of optical frequency was measured. The Fourier transform of the observed transmission spectrum is shown in Fig. 4(a). In these data we observed no oscillations as evidenced by the fact that there are no significant peaks in the Fourier transform. Resonances formed by reflections from the photonic crystal waveguide junctions and the cleaved facets were not observed in any data. We expect, based on finite-element method transmission calculations, that the transmission through a photonic crystal Y branch is about 25% over the spectral region considered here and that the transmission through a photonic crystal waveguide bend is about 99% in this spectral range.[9] We did not observe resonances between the Y branches and the facets due to the low quality of the cleaved facets of the devices used in this study.

In summary, we have demonstrated transmission through Mach–Zehnder interferometers formed from single-line defects in suspended membrane two-dimensional photonic crystal waveguides. This has been done in a series of devices with varying path length differences. We have shown that the oscillations in the transmitted intensity as a function of optical frequency are due to the interference between two arms.

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propagation through the substrate by lowering the fiber used to collect the transmitted intensity below the suspended membrane. Under these conditions, the peak at 2230 μm remains while the peak at 637 μm disappears. The symmet-